

NanoObservatory™: Earth Imaging for Everyone

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Abstract

Earth imaging has traditionally been the domain of large governments and expensive satellites. Progress in earth imaging satellite technology has focused on driving down image resolutions, decreasing re-visit times, and expanding spectral coverage. While imaging capability has increased, costs have grown exponentially, pricing many would-be science applications out of the market. Many scientific groups, especially those in countries with emerging economies, have a compelling need for earth imaging to monitor the use of natural resources, measure changes in climate, quantify and track pollution, and assist in natural disaster warning and recovery—without the high cost of a dedicated system or the restrictions imposed by sharing data from another country's system.

NanoObservatory, shown in Figure 1, is a low-cost solution for users wanting basic earth imaging for science applications. It provides multi-spectral imaging (red, green, blue) with a ground sampling distance (GSD) of 10m, and can be customized to image in other spectral ranges as necessary. The satellite resides in a 600km circular orbit between 0° and 38° inclination. From this vantage point, the satellite images a 50km x 50km area and can store consecutive images to create a seamless view. The satellite uses innovative designs for attitude determination and control (ADCS) and communications to deliver the best performance for the lowest cost. A single, off-the-shelf ground station transmits commands to the satellite and downloads images while it is overhead.

The real breakthrough with NanoObservatory is not in capabilities but in cost. Weighing only 25kg, NanoObservatory can ride as a secondary payload on other missions, lowering the cost of launch. NanoObservatory takes advantage of the low radiation environment in LEO by using commercial off-the-shelf parts in novel ways, which lowers non-recurring engineering costs. In addition, the satellite's simple command and control system requires only a basic ground station and PC for operation, making its on-going costs a fraction of competing earth imaging systems.

Many science applications do not require high-resolution imaging, but could benefit from a low-cost, dedicated Earth imaging platform. NanoObservatory fills this gap and delivers the benefits of space-based remote sensing to a new segment of underserved customers. NanoObservatory is a breakthrough technology that makes earth imaging for everyone.

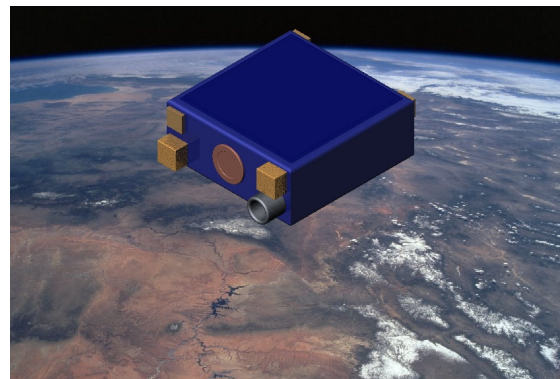


Figure 1: Rendering of NanoObservatory in low Earth orbit.

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Introduction

Earth imaging has been a key application of space technology from the beginning of space exploration. What began as primarily a military function has evolved into a global industry with civilian and commercial applications ranging from precision farming to disaster recovery. The driving force behind the commercialization of Earth imaging has been the rapid advance of satellite imaging technology. Commercial imagery is now available with resolution as fine as 61 centimeters. With the integration of the Internet into data distribution pipelines, the freshness of data has advanced significantly, making imagery available in just hours instead of days or weeks. At the same time, the re-visit rate has increased and the spectral coverage has expanded, making today's Earth imaging products abundant in both quantity and quality.

Yet with all of these advances, the Earth imaging industry has yet to see the explosion that was predicted just a few years ago.¹ There are many factors to blame for this, including strict government regulation and prohibitive costs. Because some of the imagery is of high quality or over sensitive areas, the U.S. government has intervened with legislation and regulations that prevent

U.S. companies from selling certain imagery. In other cases, such imagery of Afghanistan taken during the recent conflict (Figure 2), the government has simply entered into a deal with the imagery provider to purchase exclusive rights to all imagery of a given area before it enters the open market. In addition, the cost of imagery is still prohibitively high for many applications, with prices ranging from \$0.20 to \$1.00 per square km². The effect of strict government regulation and high costs has been to keep many important scientific applications out of the market. Earth imaging is not yet within the reach of many users and applications that could benefit from it.



Figure 2: 1m resolution image of Kandahar, Afghanistan in July 2000, courtesy of SpacelImaging.

The technological breakthrough in AeroAstro's NanoObservatory Earth imaging satellite is not in capabilities but in cost. The real breakthrough in cost is that the NanoObservatory can provide imagery at \$0.15 or less per square km and is inexpensive enough to be indigenously owned and operated by developing nations. With the capacity to produce images in three to four spectral bands at 10 meter resolution, the NanoObservatory provides imaging that is more than adequate for many scientific applications, but is not of high enough resolution to warrant government regulation.

The cost of NanoObservatory is a small price to pay to enable Earth observation, solar science, and space science applications. A recent study found that over 200 million people are affected each year by natural disasters—over seven times the number affected by armed conflict—resulting in \$50 to \$100 billion in property damage.³ Using NanoObservatory for precision farming, climate research, land use monitoring, and disaster recovery, warnings of natural disasters can be accelerated and disaster recovery efforts improved. With the cost breakthroughs brought about by NanoObservatory, Earth imaging is now within the reach of the people who need it most.

Technology Breakthroughs

System Overview

The NanoObservatory™ system provides an affordable means for collecting general usage imagery of Earth for academic, commercial, and scientific purposes. NanoObservatory is available as a turnkey solution, including the space, ground, and launch segments. The space segment is the satellite system, with a mass of 25 kg operating in a 600 km, circular orbit at any inclination, and an on-orbit lifetime of at least 3 years. This orbit provides multiple passes per day in a region of interest for image collection and downlink. NanoObservatory is capable of capturing 74 images per day with each image covering a 50 km by 50 km area at 10 meter spatial resolution in three to four visible and near-infrared bands.

The baseline satellite, shown in Figure 3, includes a RGB (Red-Green-Blue) true color imager, an ADCS system sufficient to provide a pointing error of within $\pm 7\text{km}$ (3σ), and the ability to store about 26 images at once. Possible enhancements to the baseline include upgrading from an RGB

imager to a RG-NIR (Red-Green-Near InfraRed), the addition of two zero-bias momentum wheels to enable adequate pointing control of the satellite in sun-synchronous polar orbits, and the addition of special real-time image data compression to potentially double the number of stored images. These options, however, are not included in this discussion.

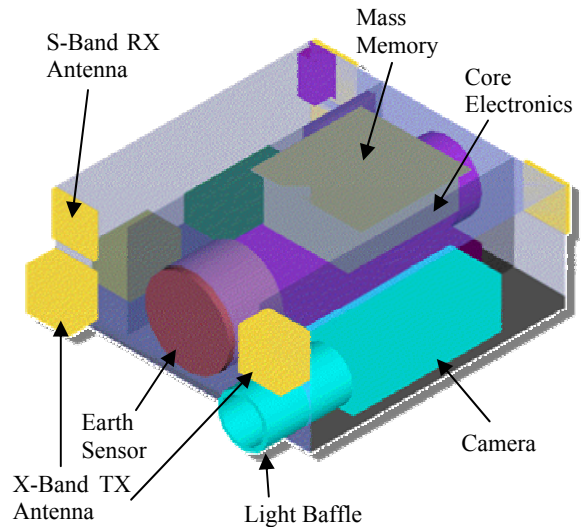


Figure 3: Diagram of NanoObservatory design.

The ground segment consists of a Master Ground Station (MGS) designed to fit the unique mission needs of each customer. The MGS is responsible for processing telemetry from the spacecraft and uploading commands as well as for downloading and processing imagery. All images are downlinked while in range of the MGS via an X-Band communications link, with sufficient RF power and bandwidth to allow a 3m groundstation to receive all the collected images during one high elevation pass over the groundstation.

NanoObservatory's low mass allows it to take advantage of low-cost launch options by riding as a secondary payload on larger missions. Using AeroAstro's Small Payload ORbit Transfer (SPORT) vehicle, NanoObservatory can reach equatorial low-Earth orbit by piggy-backing on launches

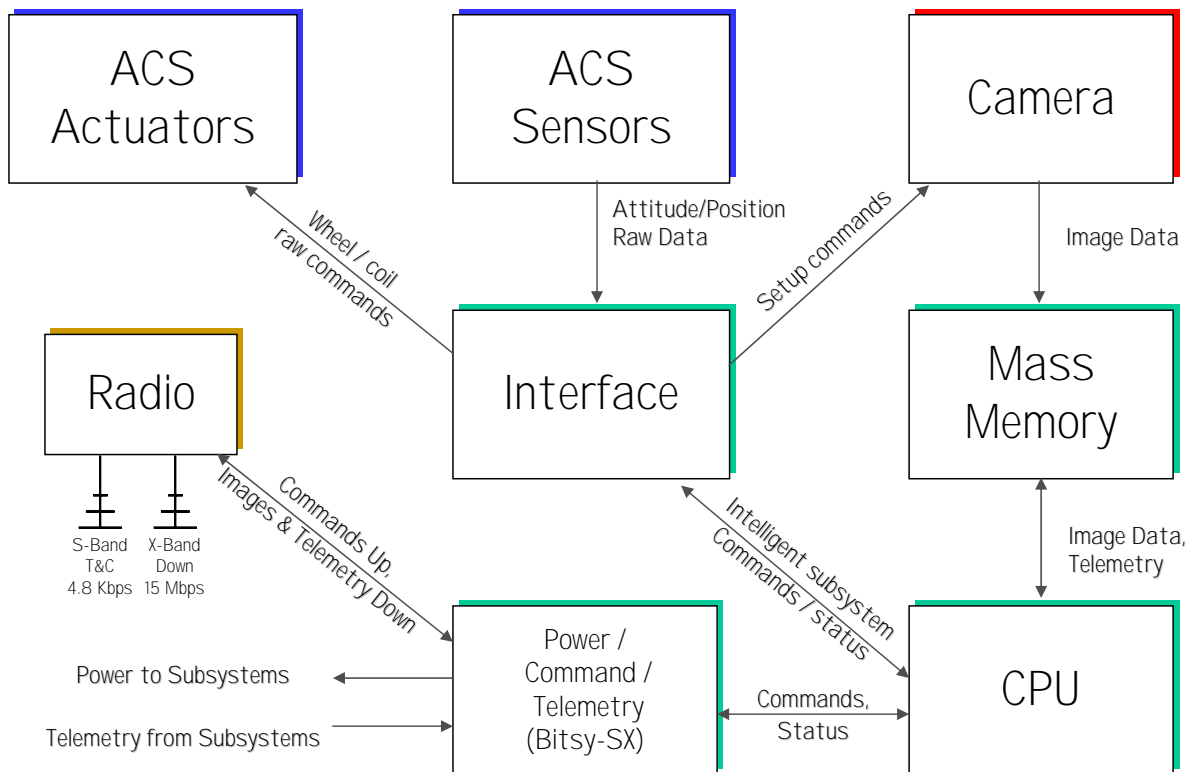


Figure 4: Functional block diagram of the NanoObservatory spacecraft.

going to geosynchronous transfer orbit (GTO). Higher inclination orbits are also obtainable through different configurations and launch vehicles.

The breakthroughs that allow NanoObservatory to provide affordable Earth imaging are: savings in mass, reduced complexity, use of inexpensive COTS components, and relaxed requirements. NanoObservatory is designed from the beginning with mass savings in mind. Simple and inexpensive components are used to reduce spacecraft complexity, lower costs, and keep mass at an absolute minimum. Where possible, performance requirements are relaxed slightly to allow for significant savings in cost and mass.

Space Segment

Camera

The centerpiece of the NanoObservatory space segment is the imager, a commercial off-the-shelf component that offers high

performance for a low cost. The baseline camera is a push-broom type imager with an 8000 x 3 (RGB) pixel linear array, only 5000 of which will be used. Each color channel uses 6 watts of power, for a total power consumption of 18 watts. The sensitivity of each of the camera's CCD filters is shown in Figure 5. The imager includes 48MB of DRAM for image buffering. The camera has a field of view of 4.8°, which translates into 50km on the ground from an altitude of 600km.

The camera can only image while in sunlight due to the fact that it is imaging in the visible spectrum. The local time at Nadir, and hence illumination conditions, vary continuously as the satellite transits the earth, making it possible to image the same area under various daylight conditions. The prime hours for imaging are when the sun is high on the horizon but not directly overhead so that shadows still can be seen. For simplicity in the satellite design, there is

no provision for Nadir off-pointing, which allows for significant cost savings.

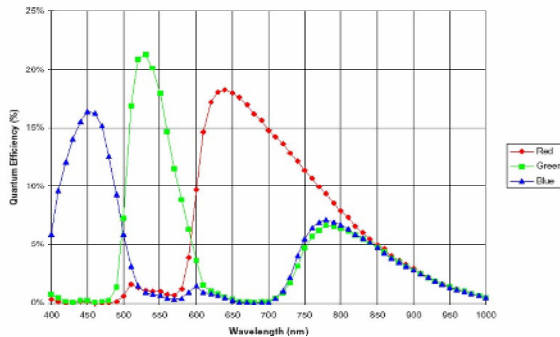


Figure 5: Bandpass frequencies of the camera CCD filters (red, green, and blue).

Data Handling

The number of images the satellite can take during any given pass is limited by the amount of mass memory available for data storage. The nominal size of the mass memory unit (MMU) on NanoObservatory is one gigabyte, with a minimum throughput rate of 83Mbps. The MMU reads directly from the camera DRAM as soon as data is received from the imager.

While the satellite is in eclipse, the MMU controller organizes the data from the camera and adds the necessary satellite attitude, attitude rate, orbital position, and time stamps onto each image frame. When the satellite is in range of the Master Ground Station, the MMU controller directs the data through the necessary I/O hardware to implement the downlink coding required to establish the necessary downlink margin.

Communications

The satellite will use an S-Band transmitter and receiver for telemetry downlink and command uplink and an X-Band transmitter for image data downlink. The S-Band uplink is designed to be able to receive a complete command upload in a single pass over a ground station, with a data rate of 4.8 kbps. The S-Band transmitter operates at

38.4 kbps and is sufficient to download all spacecraft telemetry to the Master Ground Station.

Spacecraft imagery is downloaded via the X-band transmitter to either the Master Ground Station or an optional receive-only ground station. Transmitting at 2 watts and with a data rate of 15 Mbps, the spacecraft is capable of downloading an average of 5 to 6 images per pass over a ground station, or 74 images per day.

Attitude Determination and Control

The spacecraft is stabilized such that it is capable of pointing the camera directly at the sub-satellite point below. While in normal operation, the spacecraft will maintain pitch and roll pointing to within $\pm 0.625^\circ$ (3σ) during the imaging phases. This corresponds to a difference of just under $\pm 7\text{km}$ between true and calculated image centers. The typical control accuracy to knowledge ratio is on the order of 2.5:1. The yaw control is better than $\pm 5^\circ$ (3σ). This corresponds to a yaw error angle that can still be geometrically corrected during post-processing using accurate yaw knowledge.

Satellite orbital position knowledge, together with image start/stop time stamps and attitude knowledge (position and rates) will be transmitted to the MGS. This information will allow the user to precisely determine the image center, skew angle, and shadowing at both the start and the end of the image frame. Image distortion can be removed on a line-by-line basis through linear interpolation based upon this information set.

Ground Segment

The Master Ground Station (MGS) consists of the hardware and software required to operate the NanoObservatory spacecraft. The MGS transmits commands to and

receives telemetry from the spacecraft while in operational orbit. The MGS can be located at a site of the customer's choice. Optional Receive-Only Ground Stations (ROGS) for image data reception only may be located in other sites of the customer's choice. The MGS generates and uplinks spacecraft commands, receives and displays spacecraft telemetry, and receives, processes, and displays images from the spacecraft's camera.

The MGS is capable of mission planning, scheduling, spacecraft management, and control of daily operations. The MGS provides tools to assist in the management of spacecraft functions such as the power and thermal systems, attitude control, and on-board memory storage. The diagram in Figure 6 illustrates how data flows from the MGS through the image/data processing system.

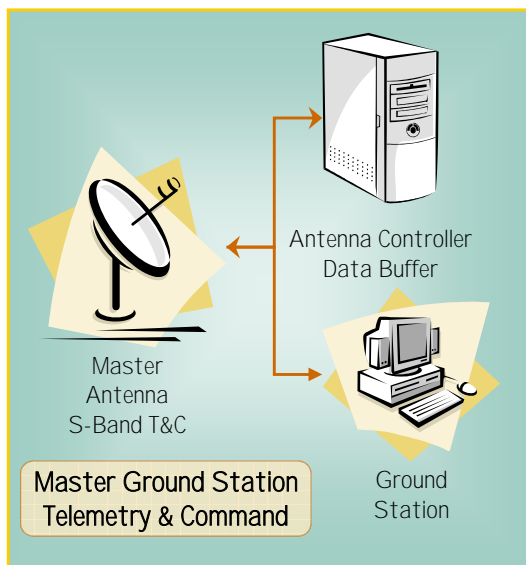


Figure 6: Dataflow at the Master Ground Station

Launch

A significant cost breakthrough with NanoObservatory is the cost of getting into orbit. At 25 kg mass, NanoObservatory is much smaller than competing Earth imaging satellites. Because of its small size and

mass, NanoObservatory can be launched as a secondary payload for a fraction of the cost of a dedicated launch.

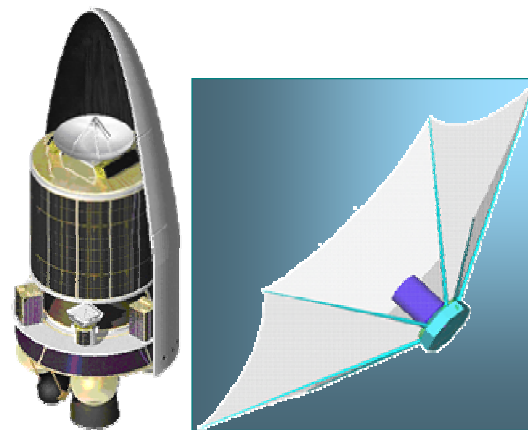


Figure 7: Left, SPORT attached to the ASAP ring. Right, SPORT with aerobrake deployed.

Orbit transfer systems, such as AeroAstro's Small Payload ORbit Transfer vehicle (SPORT) in Figure 7, can be used to move NanoObservatory from its drop-off orbit to its destination orbit, enabling the use of launches going to a variety of orbits. For example, NanoObservatory could launch on an Ariane 5 mission going to GTO and use MicroSPORT to transfer from GTO to an equatorial low Earth orbit. With such flexibility, a wide array of affordable launch options are available.

Applications Enabled

There are many science applications ideally suited for NanoObservatory that are inadequately served by other high resolution Earth imaging systems. NanoObservatory is ideal for applications that require frequent, uninterrupted, medium resolution (10 m GSD) imagery taken under variable or constant lighting conditions. Examples of these applications, shown in Figure 8, are environmental monitoring, natural disaster warning and recovery, and land use monitoring. NanoObservatory also can be adapted for solar science and space science

applications by changing the imager and attitude determination and control system.

Environmental Monitoring

Environmental monitoring applications include vegetation cover measurements, habitation studies, wetlands monitoring, and other wide area surveillance applications. Developing nations have the greatest need for environmental applications but have the least amount of money available to pay for it. Commercially available imagery is currently too expensive, too infrequent, and higher resolution than is appropriate for many environmental applications—effectively pricing them out of the market. NanoObservatory breaks through the price barrier by offering a dedicated system with a lower cost per image, more frequent coverage, and the appropriate resolution imagery for environmental monitoring applications.

Natural Disaster Warning & Recovery

A recent study by the World Meteorological Organization found that natural disasters were responsible for nearly 250,000 deaths each year. Asia was the continent most frequently hit by natural disasters, claiming 43% of the disasters, and also the most unprepared, accounting for 80% of the deaths.⁴ Regular monitoring of climate changes, land use, erosion, soil moisture content, and other factors measurable by Earth imaging can give warnings before natural disasters, such as mud slides and floods, occur.

However, some natural disasters give no warning that can be detected, such as earthquakes. In these instances, Earth imaging can be critical to recovering from disasters after they occur. Natural disasters may disrupt land based communications so that the extent of damage and areas affected cannot be easily ascertained. Earth imaging has been used on multiple occasions to

quickly determine which areas have been affected, which roads are blocked, and how to best get relief to victims. Dedicated, affordable Earth imaging through NanoObservatory allows even the poorest of countries to protect their populations and economies from unforeseen natural disasters.

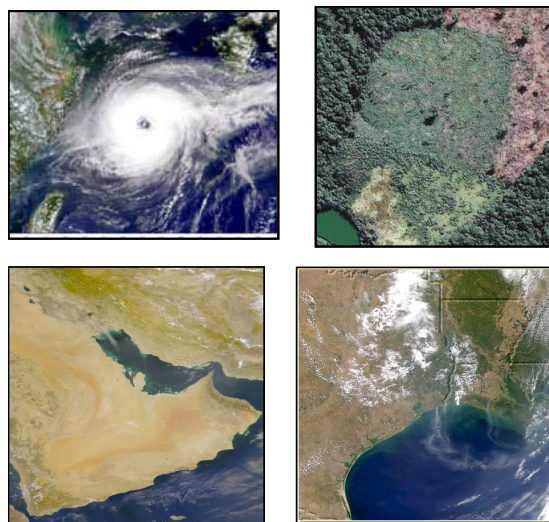


Figure 8: Examples of environmental, natural disaster, and land use applications of Earth imaging.

Land Use Monitoring

Many developing and industrialized countries have problems monitoring commercial uses of land. Surface coal mining, also known as strip mining, disturbs large areas of land and is difficult to monitor from the ground.⁵ Deforestation, illegal mining, and other violations of land use policies can be monitored and prosecuted through data collected from NanoObservatory. Developing countries in particular have had a difficult time regulating and controlling land use, which in many cases is critical to the future of their economy and environment.

Solar Science & Space Science

NanoObservatory also can be adapted from its Earth imaging mission to perform solar

science and space science missions. The baseline imager can be replaced with a camera and lens suited for star or sun imaging. Additionally, the attitude determination and control system can be modified to accommodate the different pointing and control requirements that may be needed. This allows for a number of scientific applications other than Earth imaging.

Conclusions

In the commercialization of Earth imaging, the chief barrier to progress has not been the level of image quality, freshness, or quantity, but rather the cost and availability of imagery. NanoObservatory fills a unique niche by providing Earth imaging at a cost that enables many new or under-served science and commercial applications. Cost savings are achieved by keeping the mass low, reducing complexity wherever possible, using inexpensive COTS components, and relaxing system requirements while maintaining a sufficient level of performance. With a low overall system cost, the NanoObservatory is affordable to non-space faring nations as well as universities or commercial organizations that could benefit from a dedicated Earth imaging platform. NanoObservatory breaks through the Earth imaging cost barrier and opens up the benefits of space-based remote sensing to a new and more varied constituency. NanoObservatory makes Earth imaging for everyone.

⁴ Ibid.

⁵ Monitoring Surface Coal Mining, Imaging Notes, May/June 2002.

¹How High Hopes For Profit in Space Fell Down to Earth, Wall Street Journal, page A1, June 5, 2002.

² Based on SPOT pricing for a standard 60 Km x 60 Km digital image, ranges from \$750 to \$3,400 for archived U.S. & international custom acquisition imagery respectively.

³ Statistics cited from a World Meteorological Organization study, <http://www.spacedaily.com/news/earth-02j.html>.